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Multi-Node Energy Renewal Schemes for Wireless Sensor Network With Single Base Station

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ABSTRACT:

The main objective of this paper is charging multiple sensor nodes in wireless manner. Magnetic resonant coupling based wireless energy transfer is a latest technology for providing energy to a wireless sensor network (WSN). In this paper, we exploit this multi-node wireless energy transfer technology and inspect whether the performance is better or not. We consider a wireless mobile charging vehicle (WMCV) which periodically moves inside a WSN and charging the sensor nodes wirelessly. As the problem is NP-hard, we instead propose an approximation algorithm with a provable performance guarantee if the energy consumption of each sensor during each charging tour is negligible.

KEYWORDS*- Wireless Mobile Charging Vehicle, Optimization, Adaptive Decision System, Scalability, Wireless energy transfer.*

I. INTRODUCTION

Sensors in conventional wireless sensor networks (WSNs) are mainly powered by batteries. Due to the limited energy capacity imposed on the batteries, the operational time of WSNs usually is limited. To prolong the operational lifetime of a WSN, an obvious solution is to replace the expired batteries with new ones. If the magnetic resonant coils operating at the same resonant frequency, Kurs *et al.* demonstrated that energy could be transferred efficiently from a source coil to a receiver coil via nonradioactive electromagnetic field. This makes such wireless energy transfer technology does not require line-of-sight (LOS), and is insensitive to the neighboring environment. Due to its inception, magnetic resonant coupling has quickly found in commercial applications.

By exploiting a novel technique called *strongly coupled magnetic resonances*, Kurs et al. showed that the wireless energy transfer is not only efficient but also immune to its surrounding environment [Kurs et al. 2007].

Most existing studies assumed that one mobile charging vehicle will have enough energy to charge all sensors in a WSN, and the proposed algorithms for vehicle charging scheduling thus are only applicable to small-scale WSNs. In a large-scale sensor network, the amount of energy carried by a single mobile charging vehicle may not be enough to charge all nearly expired sensors, as there are a large proportion of life-critical sensors to be charged to avoid their energy depletion. In this Paper, we will study the use of multiple mobile charging vehicles to replenish energy to sensors for a large-scale WSN such that none of the sensors runs out of energy, and each sensor can be charged by a mobile charging vehicle within its vicinity through wireless energy transfer.

In this Paper, we assume that each mobile charging vehicle can carry only a limited, rather than infinite, amount of energy. We will study a fundamental sensor charging problem in a large-scale WSN. The main contributions of this work are as follows. We first consider the problem of sensor recharging by minimizing the number of mobile charging vehicles needed, subject to the energy capacity constraint on each of the mobile charging vehicles. We then devise an approximation algorithm with a provable performance guarantee if the energy consumption of each sensor during each charging tour can be ignored; otherwise, we propose a heuristic algorithm by modifying the proposed approximation algorithm. Finally, we conduct extensive simulation experiments to evaluate the performance of the proposed algorithms.

Section 2 introduces the system model, and problem definition. Sections 3 and 4 propose an approximation algorithm and a heuristic algorithm and Section 5 concludes the article.

II. SYSTEM MODEL

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We consider a large-scale WSN, $G_s = (V_s, E_s)$, deployed for environmental monitoring or event detection, where V_s is the set of sensors and a base station. There is an edge in E_s between any two sensors or a sensor and the base station if they are within the transmission range of each other. All sensing data will be relayed to the base station through multichip relays. Figure 1 illustrates such a network. Assume that there is sufficient energy supply to the base station. Each sensor $v_i \in V_s$ is powered by a rechargeable battery with energy capacity B_i. It consumes its energy when performing sensing, data processing, and data transmission and reception.

To maintain the long-term operation of a rechargeable sensor network, the sensors in the network will be charged at certain time points by mobile charging vehicles

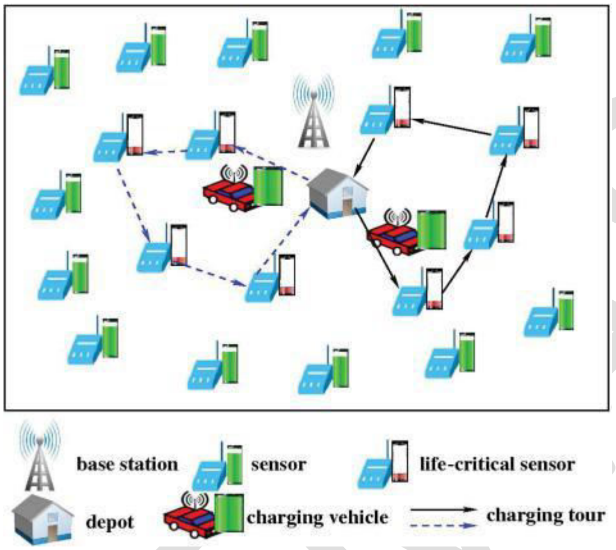

Fig. 1. A rechargeable WSN

We thus assume that there is a depot in the monitoring region, where there are a number of mobile vehicles available to meet sensor charging demands. Assume that each mobile charging vehicle has a full energy capacity *IE* and a charging rate μ for charging a sensor, and the vehicle travels at a constant speed *s*. We further assume that the mechanical movement of the vehicle is derived from its energy as well.

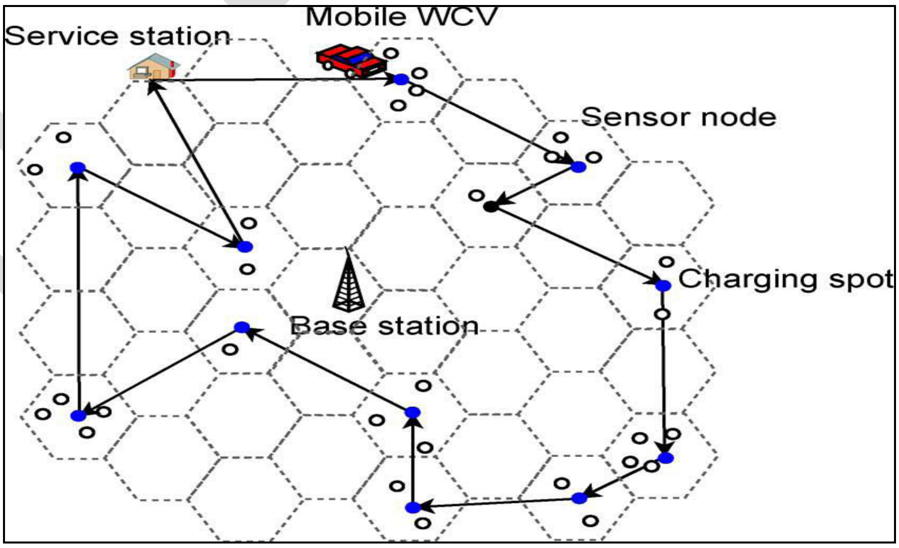

Fig. 2. Example sensor network with a mobile WCV.

Let η be the energy consumption rate of each vehicle on traveling per unit length. All mobile vehicles

will start from the depot when performing their charging duties and return to the depot after finishing their charging tours. They will be recharged at the depot and wait for the next round of scheduling. Since the energy capacity of each mobile vehicle is limited, its total travel length and the number of to-be-charged sensors by the mobile vehicle must be constrained by its energy capacity *IE*.

The residual lifetime of each sensor $v_i \in V_s$ at time t is defined as

$$l_i(t) = \frac{RE_i(t)}{\rho_i(t)} \qquad (1)$$

where $RE_i(t)$ and $\rho_i(t)$ are the amount of residual energy and energy consumption rate of v_i at time t, respectively. The base station keeps a copy of the energy depletion rate $\rho_i(t)$ and the residual energy $RE_i(t)$ of each sensor $v_i \in V_s$.

III. PROBLEM DEFINITION

Given a rechargeable sensor network $G_s = (V_s, E_s)$ consisting of sensors, one stationary base station, and a depot with multiple mobile vehicles, following the on-demand sensor energy charging paradigm, assume that at a specific time point the base station receives charging requests from the sensors within their critical lifetime intervals. The base station then starts a new round of scheduling by dispatching a certain number of mobile charging vehicles to charge these sensors so that none of sensors runs out of energy. Let V be the subset of sensors in G_s to be charged (within their critical lifetimes) in the next round ($V \subseteq V_s$) (see Figure 1). Assume that for each sensor $v_i \in V$, its energy consumption rate ρ_i does not change during each charging round (or such changes are marginal and can be ignored) and its residual energy RE_i is given (at the base station); the *minimum vehicle deployment problem* is to find a scheduling of mobile charging vehicles to fully charge the sensors in V by providing a closed tour for each vehicle such that the number of mobile vehicles deployed is minimized, subject to the energy capacity constraint *IE* on each mobile vehicle. For this defined problem, we further distinguish it into two different cases: one is that the energy consumption of each to-be-charged sensor during its charging round is not considered, and the other is that such energy consumption is taken into account.

IV. ALGORITHM FOR THE *P*-OPTIMAL CLOSED TOUR PROBLEM

This algorithm will be used as a subroutine for the minimum vehicle deployment problem in Section 5. As a special case of the p-optimal closed tour problem, when $p = 1$ is the well-known TSP problem that is NP-hard, the p-optimal closed tour problem is NP-hard as well. In the following, we start by introducing a popular technique to transform a tree into a closed tour in G. We then introduce a novel tree decomposition. We finally present an approximation algorithm for the problem based on the tree decomposition.

4.1. A Closed Tour Derived from a Tree

We first introduce the technique that transforms a tree in G to a closed tour by the following lemma.

LEMMA 4.1. *Given a node and edge weighted metric graph $G = (V, E; h, w)$ with sets V and E of nodes and edges, $h : V \rightarrow\_ R^{\geq 0}$ and $w : E \rightarrow\_ R^{>0}$, and the edge weight follows the triangle inequality, let $T = (V, E_T ; h, w)$ be a spanning tree of G rooted at r. Let C be the traveling salesman tour of G derived from T through performing the pre-order traversal on T and pruning, then the total cost $WH(C)$ of C is no more than twice the total cost $WH(T)$ of T —that is, $WH(C) \leq 2WH(T) = 2({}_{v\in V}\, h(v) + {}_{e\in ET}\, w(e))$.*

PROOF. Let $H(X)$ be the weighted sum of nodes in X, and let $W(Y)$ be the weighted sum of edges in Y, as the weighted sum $W(C)$ of the edges in C is no more than $w(e)$, and the weighted sum $H(C)$ of nodes in C is the same as the one in T .Thus, the total cost of C is $WH(C) = W(C) + H(C) \leq 2W(T) + H(T) \leq 2(W(T) + H(T)) = 2WH(T)$

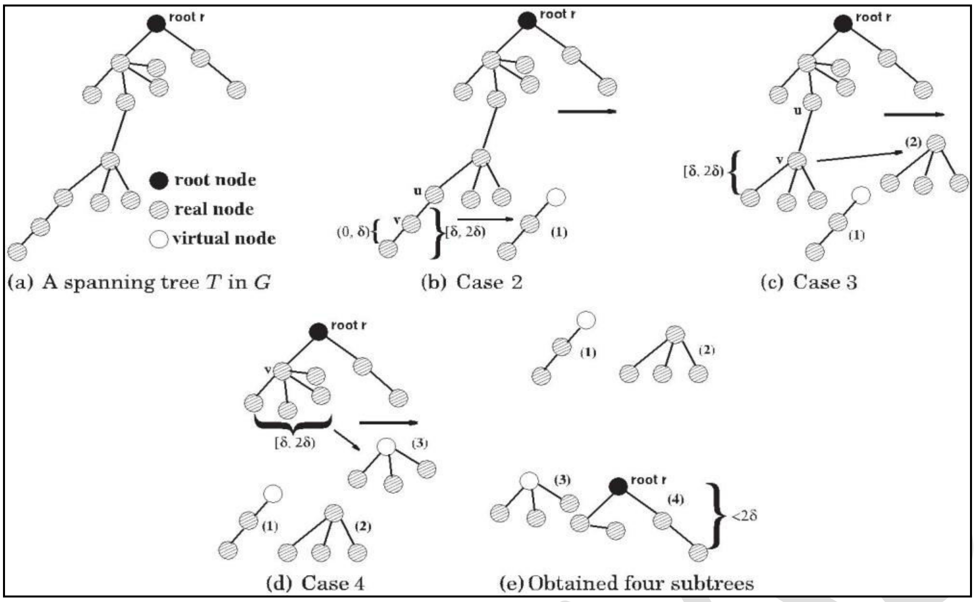

Fig. 2. An illustration of the tree decompositions.

4.3. Algorithm for Finding p-Optimal Closed Tours

Given a metric graph $G = (V, E; h, w)$ with root r and a positive integer p, we now devise an approximation algorithm for the p-optimal closed tour problem in G as follows. Let T be a minimum spanning tree (MST) of G rooted at r. The basic idea of the proposed algorithm is that we first perform tree decomposition on T with the optical cost of the result. p sub trees are

Derived from such a decomposition, and p closed tours are then derived from the p sub trees. We finally show that $p \leq p$ and the maximum total cost of any closed tour among the p closed tours is no more than 5δ.

ALGORITHM: *Finding the Optimal Number of Mobile Vehicles and Their Closed Tours Under the Sensor Energy Consumption Assumption (NMV With Eloss)*

Input: A metric graph $G = (V, E; h, w)$, a root $r \in V$, the energy capacity IE, the charging rate μ of each mobile vehicle, and the energy depletion rate ρ_i of each node $v_i \in V$.

Output: p-node-disjoint closed tours with a shared node r covering all nodes in V such that the total cost of each tour is no more than IE.

infeasible ← *false* ; /* determine the solution is a feasible solution to the problem */
Find a solution $C = \{C_1, C_2, \ldots, C_p\}$ by applying Algorithm 2 with vehicle energy capacity IE;
for *each closed tour* $C_i \in C$ **do**
    Compute $E(C_i)$ by Equation (10);
    if $E(C_i) > IE$ **then**
        infeasible ← *true* ;
    end
end
$E_{extra} \leftarrow \rho_{max} \cdot l_{max}$, where $\rho_{max} = \max_{vi \in V} \{\rho_i\}$;
while *infeasible* **do**
    A new solution C is obtained by invoking Algorithm 2 with vehicle energy capacity $IE = IE - E_{extra}$;
    $C \leftarrow C$;
    if *the new solution is infeasible* **then**
        $E_{extra} \leftarrow E_{extra} + \rho_{max} \cdot l_{max}$;
    else
        infeasible ← *false* ;
    end
end
return C and the number of mobile vehicles $p = |C|$.

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V. V.CONCLUSION

In this article, we studied the use of the minimum number of mobile charging vehicles to charge sensors in a large-scale WSN so that none of the sensors will run out of energy. We first proposed an on-demand energy charging paradigm for sensors. We then formulated the minimum vehicle deployment problem. Since the problem is NP-hard, we instead devised an approximation algorithm with a provable performance guarantee, assuming that the energy consumption of each sensor during each charging tour is neglected; otherwise, we proposed a novel heuristic by invoking the approximation algorithm iteratively. We finally conducted extensive experiments by simulations to evaluate the performance of the proposed algorithms. In our future work, we will study the minimum vehicle deployment problem when the residual lifetime of each to-be-charged sensor is very short for which we will devise new algorithms, and we believe that the charging order of sensors in each charging tour will be the key in the design of such algorithms.

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